

Experimental study to explore the ^8Be induced nuclear reaction via the Trojan Horse Method

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To explore a possible indirect method for ^8Be induced astrophysical reactions, the $^9\text{Be} = (^8\text{Be} + n)$ cluster structure was studied via the Trojan Horse Method. It is the first time to study a super short life nucleus ^8Be via the Trojan Horse Method, and it is the first time to make a valid test for $l = 1$ Trojan-horse nucleus. The ^9Be nucleus is assumed to have a $(^8\text{Be} + n)$ cluster structure and used as the Trojan-horse nucleus. The ^8Be nucleus acts as a participant, while the neutron is a spectator to the virtual $^8\text{Be} + d \rightarrow \alpha + ^6\text{Li}$ reaction via a suitable 3-body reaction $^9\text{Be} + d \rightarrow \alpha + ^6\text{Li} + n$. The experimental neutron momentum distribution inside ^9Be was reconstructed. The agreement between experimental and theoretical momentum distribution indicates that there should be a $(^8\text{Be} + n)$ cluster structure inside ^9Be . Therefore the experimental study of ^8Be induced reactions, for example the experimental measurement of the $^8\text{Be} + \alpha \rightarrow ^{12}\text{C}$ reaction proceeding through the Hoyle state, is possible.

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INTRODUCTION

Nuclear reactions induced by ^8Be are very important for the study of astrophysical nucleosynthesis, especially for the production of C-12 via the Hoyle state, and provide a new possible way to solve the lithium puzzles in nuclear astrophysics.

The production of the element carbon is one of the key reactions in stellar nucleosynthesis. Ordinarily, the probability of the triple α process is extremely small. The most abundant isotope, ^{12}C , is created through the formation of the ^8Be ground state as intermediate state. However, ^8Be has a very short lifetime against α decay, implying that it should almost always break up rather than become the seed for carbon. The astrophysicist Fred Hoyle recognized that the observed abundance requires an accelerating mechanism and he predicted the existence of an excited state in ^{12}C close to the threshold for $^8\text{Be} + ^4\text{He}$ fusion [1]. This resonance greatly increases the probability that an incoming α will combine with ^8Be to form ^{12}C . The excited state, with $E^* = 7.6\text{MeV}$, $J^\pi = 0^+$, indeed exists, and is often referred to as the "Hoyle state". But, there is no way to directly study the reaction $^8\text{Be} + \alpha \rightarrow ^{12}\text{C}^*(\text{Hoyle} - \text{state}) \rightarrow ^8\text{Be} + \alpha$ up to now.

To solve the lithium puzzle in nuclear astrophysics, there will be a new possible way when taking into account the ^8Be induced reactions. The observed ^6Li abundance in low-metallicity stars is about three orders of magnitude large than that predicted from standard big bang

nucleosynthesis. In addition, ^7Li observations lie a factor 3-4 below the big bang prediction [2, 3]. The fusion of two α into ^8Be requires 0.093 MeV. While there is a resonance in ^{10}B at about 0.1 MeV above the $^8\text{Be} + ^2\text{H}$ fusion threshold. So this resonance maybe markedly increase the ^6Li production by reaction $^8\text{Be} + ^2\text{H} \rightarrow ^4\text{He} + ^6\text{Li}$, when the temperatures and densities were suitable in some astrophysical environment. On the other hand, the $^8\text{Be} + ^7\text{Li}$ reaction proceeding maybe have effect for destroying ^7Li .

Although the nuclear reactions induced by ^8Be are so important, however due to the short life of ^8Be which is only 10^{-16}s , it can neither be used as a beam nor as a target by current technical means. Therefore, up to now, the ^8Be induced nuclear reactions can not be studied directly.

The Trojan-horse method (THM) [4] provides a possible way for indirect research of ^8Be induced nuclear reactions by using ^9Be as the Trojan horse nucleus, assuming that ^9Be has a $(^8\text{Be} + n)$ cluster structure [5, 6] with the orbital angular momentum $l = 1$.

The THM is an indirect approach to determine the energy dependence of S factors of astrophysically relevant two-body reactions. The aim of the THM is to extract the cross-section of an astrophysically relevant two-body reaction

$$A + x \rightarrow C + c \quad (1)$$

from a suitably chosen reaction

$$A + a \rightarrow C + c + b \quad (2)$$

with three particles in the final state assuming that the Trojan-Horse a is composed predominantly of clusters x and b . If the $C+c$ system is considered as an excited state of the compound system B . The formulation Eq.(3) is the direct relation of the three-body cross-section to the two-body cross-section for partial wave l after selecting the quasi-free events [7, 8].

$$\frac{d^3\sigma}{dE_{Cc}d\Omega_{Cc}d\Omega_{Bb}} \propto \text{KF} \cdot |W(\vec{Q}_{Bb})|^2 \cdot \left(\frac{d\sigma}{d\Omega}\right)_{c.m.}^{\text{HOES}} \quad (3)$$

KF is a kinematical factor containing the final state phase space factor and is a function of the masses, momenta and angles of the outgoing particles. $|W(\vec{Q}_{Bb})|^2$ is the momentum distribution of the spectator b inside the Trojan-horse nucleus a . The term $\left(\frac{d\sigma}{d\Omega}\right)_{c.m.}^{\text{HOES}}$ is the differential two-body cross section induced at energy $E_{c.m.}$ given in post-collision prescription by $E_{c.m.} = E_{Ax} = E_{Cc} - Q_{2body}$. The variable E_{Cc} is the relative energy between the outgoing particles and Q_{2body} is the Q-value of the virtual two body reaction. Using the Eq.(3), we can reconstruct the momentum distribution of $|W(\vec{Q}_{Bb})|^2$ via THM.

In this paper, the THM was applied to the ${}^9\text{Be} + d \rightarrow \alpha + {}^6\text{Li} + n$ reaction. The ${}^9\text{Be}$ nucleus was assumed as $n + {}^8\text{Be}$ cluster structure and used as the Trojan-horse nucleus. The ${}^8\text{Be}$ nucleus acts as a participant, while the neutron is a spectator to the virtual ${}^8\text{Be} + d \rightarrow \alpha + {}^6\text{Li}$ reaction. The experimental neutron momentum distribution inside the Trojan-horse nucleus ${}^9\text{Be}$ would be reconstructed. This can give a test if there is a cluster structure of ${}^9\text{Be} = ({}^8\text{Be} + n)$ inside ${}^9\text{Be}$, which is a feasibility study for the further research work of ${}^8\text{Be}$ related nuclear reactions. And it is also worth to mention that this is the first experiment to use a $l = 1$ nucleus as Trojan-horse nucleus.

EXPERIMENTS

A beam of ${}^9\text{Be}$ at 22.4 MeV was provided by the HI-13 tandem accelerator at China Institute of Atomic Energy. A strip of deuterated polyethylene target CD_2 of about $160\mu\text{g}/\text{cm}^2$ in thickness and about 1 mm in width was oriented with its surface perpendicular to the beam direction. Using the strip target limited the horizontal width of the beam spot in 1 mm to decrease the angle error.

A position sensitive detector (PSD_1) was placed at $15^\circ \pm 5^\circ$ to the beam line direction and about 240 mm from the target. In the other side of the beam line, a DPSD (Dual Position Sensitive Detector, consisted of PSD_u in the upside and PSD_d downside) was used at

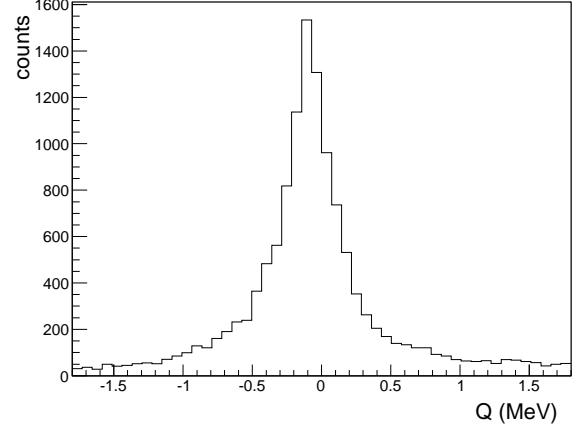


FIG. 1. Experimental Q-value for the ${}^2\text{H}({}^9\text{Be}, \alpha {}^6\text{Li})n$ reaction peaked at ~ -0.1 MeV.

$8.7^\circ \pm 5^\circ$ and about 250 mm distance from the target. The trigger for the event acquisition was generated by events having particle multiplicity larger than 1. Energy and position signals for the detected particles were processed by standard electronics and sent to the acquisition system for online monitoring and data storage for offline analysis.

DATA ANALYSIS

For the angular calibration, an equally spaced grid was mounted in front of each detector and the angular position of each grid inside the scattering chamber was determined by using an optical system. The position and energy calibrations were performed by means of a standard α source, the ${}^{12}\text{C}({}^6\text{Li}, {}^6\text{Li}){}^{12}\text{C}$ and ${}^{197}\text{Au}({}^6\text{Li}, {}^6\text{Li}){}^{197}\text{Au}$ scattering with ${}^6\text{Li}$ beam at 15 and 10 MeV, and the ${}^{197}\text{Au}({}^9\text{Be}, {}^9\text{Be}){}^{197}\text{Au}$ scattering with ${}^9\text{Be}$ beam at 8 and 22.4 MeV.

After position and energy calibration, the selection of the ${}^2\text{H}({}^9\text{Be}, \alpha {}^6\text{Li})n$ reaction channel was performed. We assume all those particles detected by PSD_1 are ${}^6\text{Li}$, all particles detected by PSD_u (in the upside of the DPSD) are α , and the third particles calculated with ${}^2\text{H}({}^9\text{Be}, \alpha {}^6\text{Li})n$ three-body reaction kinematic equations are n . In order to understand the experimental data, a set of simulation system was established for the experimental setup based on Geant4 [9, 10]. These right events were selected with the help of the simulation system. The Q-value of the ${}^2\text{H}({}^9\text{Be}, \alpha {}^6\text{Li})n$ reaction was reconstructed by means of the momentum and energy conservation. The experimental spectrum of the Q-value is shown in Fig.1, for which a peak centered about -0.1 MeV was obtained in agreement with the expected theoretical value. The majority of events would be considered in the reaction channel of interest when the Q-value was

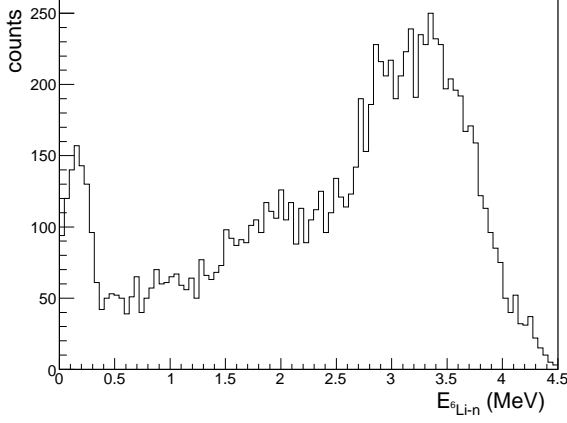


FIG. 2. Relative energy of ${}^6\text{Li} - n$ spectra. There is a peak about 0.2 MeV belonging to the 7.45 MeV excited states of ${}^7\text{Li}^*$.

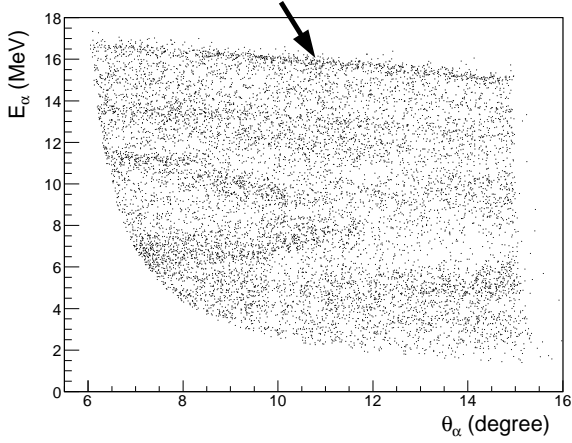


FIG. 3. E_α vs θ_α relative two-dimensional plots. The events, which appears a curve and were indicated by an arrow, mainly came from the sequential mechanism reaction ${}^9\text{Be} + {}^2\text{H} \rightarrow {}^7\text{Li}^* + \alpha \rightarrow {}^6\text{Li} + n + \alpha$.

selected from -0.9 to 0.7 MeV.

The next step is the quasifree mechanism identification of the $\alpha + {}^6\text{Li} + n$ exit channel. There is a peak of $E_{6\text{Li}-n} = 0.2$ MeV in Fig.2, which belongs to the 7.45 MeV excited states of ${}^7\text{Li}^*$. It means that the events mainly came from the sequential mechanism reaction ${}^9\text{Be} + {}^2\text{H} \rightarrow {}^7\text{Li}^* + \alpha \rightarrow {}^6\text{Li} + n + \alpha$. Because α came from the two-body reaction ${}^9\text{Be} + {}^2\text{H} \rightarrow {}^7\text{Li}^* + \alpha$, the events appears a curve in the E_α vs θ_α relative two-dimensional plots (see Fig.3). So those events, which were around the curve indicated by an arrow in Fig.3, would be eliminated for the quasifree mechanism identification.

In this paper, we expect the Trojan-horse nucleus to be ${}^9\text{Be} = {}^8\text{Be} + n$. But, in fact, the neutron can

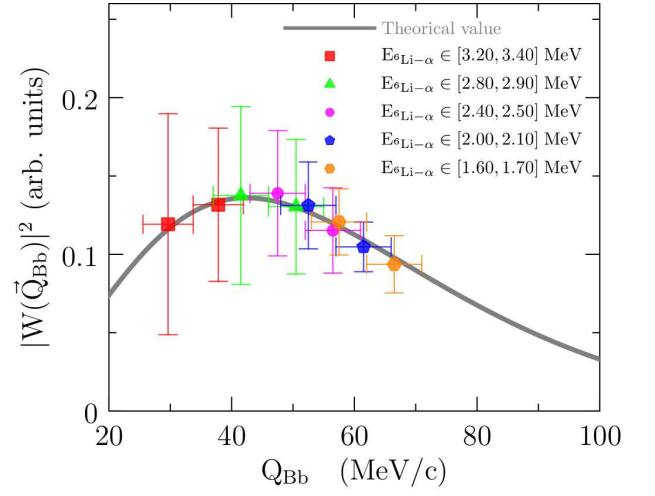


FIG. 4. Comparison between the experimental neutron momentum distribution (different color solid symbols) and theoretical one (grey line). The different color solid symbols come from cutting different range of ${}^6\text{Li} - \alpha$ relative energy and extracting the neutron momentum distribution. The error bars include only the statistical one.

also come from the Trojan-horse nucleus ${}^2\text{H} = p + n$. An intermediate process was assumed exist when those events meet the quasifree condition [11]. Three criteria for the experimental identification of the quasifree mechanism were introduced [12]. Two different Trojan-horse nucleus situation were respectively applied to these criteria. The events will be selected when they are agree with the Trojan-horse nucleus as ${}^9\text{Be} = {}^8\text{Be} + n$, and be eliminated when they are agree with the Trojan-horse nucleus as ${}^2\text{H} = p + n$.

EXTRACT OF THE NEUTRON MOMENTUM DISTRIBUTION

The term $\left(\frac{d\sigma}{d\Omega}\right)_{c.m.}^{\text{HOES}}$ in Eq.3 represents the nuclear part of the differential cross section for the virtual two-body reaction ${}^8\text{Be}({}^2\text{H}, \alpha){}^6\text{Li}$ that in post-collision prescription occurs at an energy

$$E_{c.m.} = E_{6\text{Li}-\alpha} - Q_{2b},$$

where $E_{6\text{Li}-\alpha}$ is the ${}^6\text{Li} - \alpha$ relative energy and Q_{2b} is the two-body Q value.

To reconstruct the neutron momentum distribution, a small ${}^6\text{Li} - \alpha$ relative energy window (about 100 keV) was selected. In such a small energy window, $\left(\frac{d\sigma}{d\Omega}\right)_{c.m.}^{\text{HOES}}$ can be considered constant. Thus the experimental $|W(\vec{Q}_{Bb})|^2$ distribution was extracted by dividing the three-body coincidence yield by the kinematic factor. The results are showed in Fig.4 with the different color solid symbols.

RESULTS AND DISCUSSION

In Fig.4, the theoretical neutron momentum distribution was calculated based on assuming ${}^9\text{Be}$ nucleus as $n + {}^8\text{Be}$ cluster structure with the orbital angular momentum $l = 1$. To solve the Schrödinger equation we applied the Wood-Saxon potential with the standard values for the radius parameter and diffuseness while the potential well depth was fixed using the ${}^8\text{Be}-n$ binding energy. The orbital angular momentum of neutron was assumed to be unity because $J^\pi = \frac{3}{2}^-$ for the ground state of ${}^9\text{Be}$. The agreement between experimental and theoretical momentum distribution indicates the $n + {}^8\text{Be}$ cluster structure of ${}^9\text{Be}$, and represents a very strong check for the existence of the quasideuteron mechanism in the present data.

In advance, there will be a possible method to study ${}^8\text{Be}$ induced reaction in experiment via THM by using the ${}^9\text{Be} = (n + {}^8\text{Be})$ as TH nucleus. One interesting work, studying the nature of Hoyle-state in Carbon-12 [1, 13] through the reaction of ${}^8\text{Be} + \alpha \rightarrow {}^{12}\text{C}^*(\text{Hoyle-state}) \rightarrow {}^8\text{Be} + \alpha$ in experiment, will be possible to be done at the next step.

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